Radiotherapy Dosimetry Audits in Taiwan Hospitals

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Research

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Abstract

Purpose: This study examines the practice of the regulation of Standards for Medical Exposure Quality Assurance (SMEQA) in Taiwan based on on-site quality audit for radiation therapy systems from 2016 to 2019.

Methods and Materials: about 81 radiation therapy departments, 141 medical linear accelerators, 9 gamma knifes, 34 high dose rate brachytherapy systems, 20 Tomotherapys and 6 Cyberknives were audited yearly. The inspection was implemented in two stages. Data collection and analysis for each institute's documents including QA operating procedure, ion chamber and electrometer calibration reports, and a questionnaire relating to machine type and staffing, were requested first and reviewed by specially trained auditors. On-site measurements of SMEQA core items, including beam output, beam profile and energy constancy for external beam therapy systems, and the source strength, positioning and timer accuracy for brachytherapy systems were audited second. More than 300 photon beams were measured from linacs, Gamma knives, Cyberknives and Tomotherapys, and more than 400 electron beams from linacs each year.

Results: The radiation treatment resource is about 8.9 therapy machines or 7.5 MV/MeV/ion beam therapy machines per million population, respectively, and there are on average about 1.20 medical physicists per radiation therapy unit in Taiwan. There were more than 78% and 75% of photon and electron beams respectively from linacs with deviations measured to the stated reference-point dose within 1.0%. Photon beams have lower beam quality measurement deviations than electron beams, and more than 90% of photon beams from linacs were within 1.0%. Including in-plane and cross-plane measurements, more than 90% and 85% of photon and electron beams respectively with flatness consistency within 1.0%. Beam symmetry as an absolute value has more than 75% of measurements within 1.0%. All audit measurements in this study were within the SMEQA acceptance criteria.

Conclusions: On-site machine QA audits have been implemented from 2016 to 2019 for all radiation therapy units each year. The measurement results have shown a high quality machine performance in Taiwan.

Background

The need for dosimetric and geometric accuracy has always been recognized as important in radiotherapy. ICRU recommendations state that the dose delivery to the primary target should have accuracy of at least ±5% of the prescribed value [1]. Considering the complex process involved in delivering a dose to a target, quality assurance (QA) at each step must be implemented with standards required to deliver the treatment in an accurate and consistent manner. One method for ensuring dosimetric consistency and improved accuracy is the quality audit. However, before the audit is implemented, standards for machine QA including the item, frequency and criteria should be established.

Radiotherapy dosimetry audit has been developed for a long time. The IAEA introduced the first postal dosimetry service in 1966. The Imaging and Radiation Oncology Core-Houston (IROC-H) was implemented in 1977. The ESTRO was proposed in 1991. The Quality Assurance Network for radiotherapy (EQUAL) project started in 1998 [2–6]. According to the IAEA Dosimetry Audit Network (DAN), 45 organizations in 39 countries confirmed operating dosimetry audit services for radiotherapy in 2017 [7].

In Taiwan, according to the Ionizing Radiation Protection Act (IRPA), the Standards for Medical Exposure Quality Assurance (SMEQA) regulations were implemented in 2005 by the Atomic Energy Council (AEC). At that time all medical linacs, Co-60 teletherapy systems and high dose-rate (HDR) brachytherapy units using radioactive material were included. Now all gamma knives, Cyberknives (Accuray Inc., Sunnyvale, CA), Tomotherapys (Accuray Inc., Sunnyvale CA), X-ray simulators, mammography systems, computed tomography systems (CT) and CT simulators were also included. According to SMEQA regulations, all included devices must establish QA programs approved by the AEC to improve radiological diagnosis and therapy quality and reduce unnecessary radiation exposure received by patients. According to the SMEQA, QA programs shall include the QA organization, operating procedures, items checked, frequency, data recording worksheets and policy when the QA result deviates from the criteria. Yearly on-site review by an AEC officer is conducted for on-going QA programs since the SMEQA was implemented.

The QA frequency, procedures and tolerance for medical therapy devices in the SMEQA refer to the American Association of Physicists in Medicine (AAPM) reports [8–11] and recommendations from vendor acceptance and commissioning procedures. There are now 36 QA medical linac procedures for example; including dosimetry, mechanical and safety must implement according to the frequency (daily, monthly or annual) assigned in the SMEQA. The reference-point dosimetry method is requested by AEC and shall follow the well-established protocol, e.g. AAPM TG-21 [12], TG-51 [13] or IAEA TRS-398 [14] for linac, and AAPM TG-148 [10] for Tomotherapy, and AAPM TG-43 [15] for brachytherapy system. In Taiwan, all reference-point doses for external beam treatment are traceable to the primary standards. The ion chamber calibration factors, including the N_x (derived from N_k) used in TG-21, and the $N_{D,\,W}^{60-Co}$ used in TG-51 and TRS-398, were provided directly by the National Radiation Standard Laboratory (NRSL), a primary standards dosimetry laboratory (PSDL), with expanded uncertainty at k = 2 about 1%. The ^{192}Ir is the source exclusively used for HRD brachytherapy in Taiwan. Well-type chambers with air kerma calibration factors provided by NRSL, with expanded uncertainty about 2.8%, were used for the source strength measurements.

After 10 years' experience in conducting SMEQA, an on-site quality audit project was carried out from 2016 to 2019, in order to examine the SMEQA practice, to assist clinical departments in improving quality in using medical exposure systems, and determine the development needs of regulation standards. All radiotherapy departments in Taiwan (about 81 in 2019) were included with yearly audit measuring the SMEQA core items including beam output, energy, uniformity, source strength, positioning et al. For about 141 linacs, 9 Gamma knifes, 6 cyberknives, 20 Tomotherapys and 34 HDR brachytherapy systems were

Materials And Methods

Data collection and analysis

Quality audit is proactive. Before performing on-site quality audit all medical therapy devices included in the SMEQA for each institute were asked to provide documents including the QA operation procedure, ion chamber and electrometer calibration reports from NRSL, reference dosimetry method and worksheet parameters for the calibration protocol. In addition, a questionnaire relating to machine type, AEC licensing date for therapy system, beam energy, MLC type, treatment planning system type, QA tools and staffing et al was ask to fill and send back to the audit team.

The parameters for each beam in the worksheets provided by the institution were reviewed by well-trained auditors. An output measurement worksheet was created for each beam with the form designed by the audit team and parameters set according to the calibration protocol used by the institution. Discussion or revision request would send by the auditor if there were some parameters inappropriately used. Prior to the audit measurements, the institution is asked to verify that the therapy unit is properly calibrated.

To track and check the on-going dosimetric QA procedure for each department, all QA devices and equipment for QA measurements were provided by the department their own, and these were validated by the auditors before audit. In addition, according to government regulations, each of the ion chamber and electrometer used for the QA procedure must respectively has a calibration certificate with issued date within 2 years by the NRSL. Parameter review and equipment validation can prevent potential errors in using the reference dosimetry protocol, and provide advice on improvement, where appropriate.

Quality audit procedure

The procedures and criteria audited include those listed in Table 1. Reference-point measurements were made for all linacs and Tomotherapy systems using 0.6 cc Farmer type ionization chamber and homogeneous phantoms. Reference conditions for the determination of absorbed dose to water was checked on-site according to the reference dosimetry protocol used by the institution. Source strength measurement for brachytherapy system was made with well-type chamber, and the source(s) was placed centrally in the chamber at the most sensitive spot which has the same location as the calibration report done by NRSL. Central axis dosimetry parameter constancy, i.e., beam quality check, was implemented by comparing the stated TPR_5^{15} (or TMR_5^{15}) and the $\mathrm{PDD}_{\mathrm{d}\approx 80\%\mathrm{PDD}}$, respectively for x-ray and electron beams. Beam flatness consistency and beam symmetry, i.e., beam uniformity check, were implemented for both in-plane and cross-plane profiles at 10 cm depth and d_{max} for x-ray and electron beams, respectively, by the 80% of a 20×20 cm^2 field for linac. Consistency with the baseline is specifically associated with flatness, and symmetry tolerance is regarded to the absolute value. Commercialized two-dimensional dose measurement tool is usually used for beam uniformity measurements. Consider the beam profiles for beams without flattening filter, including Tomotherapy and linacs with flattening-filter-free (FFF) beams, beam profile constancy method stated in AAPM TG-142 [9] was used by comparing the [illegible] e same points within the 80% of an agreed upon field size.

As Gamma knife and Cyberknife are specially designed for stereotactic radiosurgery or stereotactic radiotherapy, the QA item of coincidence of radiation and mechanical isocenter was included in the audit measurement. Consider the Tomotherapy delivery technique simultaneously with the gantry rotation and the treatment couch longitudinal motion, couch motion accuracy for Tomotherapy was included.

EBT or RTQA radiochromic film was used for source position check. All Audits follow the QA operation procedure provided by the institution that has been validated by the AEC.

Results

In Taiwan, there are 210 radiation therapy units including linacs, Tomotherapys, Cyberknives, Gamma knives, HDR brachytherapy and multi room proton therapy systems in 2019. External-beam radiotherapy (EBRT) treatment equipment was dominated by linacs with 80.1% of all EBRT treatment units being linacs. For linacs, 97.7% of beam energies were 6 MV (44.7%), 10 MV (38.5%) and their FFF mode.

The radiation treatment resource is about 8.9 therapy machines or 7.5 MV/MeV/ion beam therapy machines per million population, respectively in Taiwan. And there are on average about 1.20 medical physicists per radiation therapy unit. Medical physics society in Taiwan (CSMPT: Chinese Society of Medical Physics, Taipei) holds professional certification examinations every year. Medical physicists must have a master's degree or above and have undergone 2–3 years of clinical professional training to participate in this certification examination.

All audit measurements in this study were within the acceptance criteria of SMEQA.

Reference point and beam quality measurements

AAPM TG-21 is the most used reference dosimetry protocol for linac output calibration (67.4%). However, for increasingly more new installed linacs have FFF beams, because the addendum report to the AAPM’s TG-51 protocol [16] has consider the application to FFF beams, so the facilities that use the TG-51 protocol as the basis for dose calibration are gradually increasing. Additionally, as the IAEA TRS-398 is the only present code on standards of absorbed dose to water for proton and heavy-ion beams, therefore, several facilities that have installed or intend to install particle therapy systems are changing the protocol for using TRS-398 as the dose calibration protocol to facilitate the integration of the calibration system.

More than 300 photon beams from linacs, Gamma knives, Cyberknives and Tomotherapys, and more than 400 electron beams from linacs each year were measured and the results were shown in Figs. 1 and 2. According to the SMEQA criterion, deviations of measurements were classified at 0.5% interval. For reference-point measurements, there were more than 78% and 75% of photon and electron beams respectively from linacs with deviations of measured to stated dose within ± 1.0% (Fig. 1A). Cyberknife with similar beam delivery control systems as linac has similar reference-point dose deviation (Fig. 1B).

For beam quality measurements, photon beams have lower deviations than electron beams. More than

in ± 1.0% (Fig. 2A). Although electron beams with higher deviations in depth dose, all deviations in depth compared to the stated depth dose parameter were within 2 mm.

Beam uniformity

Including in-plane and cross-plane, about 600 photon and 850 electron profiles from linacs were measured each year. More than 90% and 85% of photon and electron measurements respectively with flatness consistency ≤ ± 1.0% (Fig. 3A). Beam symmetry as an absolute value, regardless of baseline, have more than 75% of measurements ≤ ± 1.0% (Fig. 3B).

HDR brachytherapy QA measurements

The measured reference air kerma rate deviation to the vendor's certificate was determined. For 117 measurements in the study period, most of the deviations were within ±3%, except in one case, which was − 3.2%, being still within the ±5% source calibration uncertainty quoted by the vendors. All measurements of source transit velocity consistency were within 1 sec, and the timer accuracy were within 1 sec/min. The source positioning accuracy was measured using more than two source dwell positions (±30 mm), and all deviations were within 1 mm.

Mechanical motion accuracy

All deviations of couch motion for Tomotherapy, Cyberknife and Gamma-knife were within 1 mm, and the radiation isocenter deviations relative to mechanical isocenter and imaging isocenter for Gamma-knife and Cyberknife were within 0.3 mm and 1 mm, respectively.

Discussion

Dosimetry audit is recognized as an important role in the development and safety of radiotherapy. According to the Taiwan SMEQA government regulation, it is mandatory for radiation departments to establish their QA program and implement all QA items listed in the SMEQA since 2005. About one fourth of the countries performing audits are for the reasons of government regulations [7]. Although the government regulation exists in Taiwan, the lack of framework to provide routinely dosimetry audits, an on-site dosimetry audits supported by governmental agency was implemented for all radiation therapy units from 2016 to 2019. The core items in the SMEQA were included.

A comprehensive quality assurance should cover the whole radiotherapy process, such as patient positioning, treatment planning, patient-specific dosimetry measurements and machine performance checks. However, routine machine QA is fundamental to assure and maintain that the machine characteristics do not deviate significantly from their baseline values set at the time of acceptance and commissioning, and to fulfill the needs for dosimetric accuracy less than ±5% of the prescribed dose. The SMEQA regulations are set based on the requirements of machine QA.

Dosimetry audit can be performed by postal dosimeters, usually based on the thermoluminescent dosemeter (TLD) or optically stimulated luminescent dosemeter (OSLD) methods, e.g. as organized by the IAEA and the IROC-H. Another method of dosimetry audit is on-site visits using ionization chambers and appropriate phantoms. On-site visits with directly acquired measurement readings have lower uncertainties, allow immediate feedback, discussion, and adjustment in a timely manner. Consider the hospital distribution is relatively concentrated in Taiwan, audit with on-site visit was adopted. The on-going dosimetric QA procedure and measurement devices performed by each department are tracked and checked using their own measurement tools. In this manner, the measurement data were acquired and the QA procedures, devices and protocol parameters audited and validated.

Treatment resource and medical physicist staffing

The treatment resource in Taiwan is about 7.5 MV/MeV/ion beam therapy machines per million population, which is roughly similar to Australia and France [17, 18]. According to the IAEA radiotherapy practice survey [19], the staffing levels for those departments without dosimetrists there were on average 1.3 medical physicists per treatment unit, and this level is at the low end range compared with IAEA recommendations [20]. From this study, there were on average 1.2 medical physicists per treatment unit in Taiwan, this level is lower than the worldwide average, although the treatment resource in Taiwan is much higher than the worldwide average. This survey reflects that radiation oncology medical physicists in Taiwan generally are overworked, just like the reports from IAEA worldwide survey and the Asia Pacific region survey [18, 19].

Reference point and beam quality measurements

Most of the measured-to-stated doses ratios for the reference-point measurements were within ±1.0% (Fig. 1), showing that no major systematic errors exist. All reference-point values lay within ±2% of unity. Linacs have shown more stable distributions in output than Tomotherapy systems. The mean differences and standard deviations (SD) in 2017 from this study were 0.03% and 0.68% for linac photon beams, and were 0.01% and 0.75% for electron beams, respectively. These results are similar to the reference dosimetry audit report in the UK since 2003 that with the mean differences and SDs of 0.3% and 0.4% for MV photon beams, 0.3% and 0.7% for electron beams [21]. These results are better than the 2016–2018 results from the IAEA/WHO postal dose audit for low-income and middle-income countries world-wide [22]. From Fig. 2, photon beams have shown smaller variations in beam energy than electron beams. For electron beams, different combinations of depths were selected for checking beam quality, and the selected depth of about 80% PDD may has larger fall-off gradient than photon beams, that makes higher measurement uncertainty for electron beams than photon beams. However, all deviations in depth were within 2 mm.

Homogeneous solid phantoms were used in this measurement, more than 50% institutions in Taiwan using RW3 white water (PTW-Freiburg, Germany) for dosimetry measurements. Tello's study showed that solid phantom materials could cause a range of 3% – 4% in the dose relative to the dose determined from measurements in water [23]. Attention should be paid before any solid phantom material is used as a water substitute. A solid-phantom-to-water correction factor was asked to apply during the document review process if this phantom material is not used in the reference dosimetry protocol. The ion chamber measurement ratios between solid phantoms and water were suggested to determine the phantom-to-water conversion factor [24].

In addition to SMEQA system establishment and education and training implementation, the machine quality is also closely related to machine maintenance implementation. Taiwan is a densely populated area, and the resources spatial distribution is also dense. Vendor maintenance teams are able to arrive on site within a short time, to repair machine malfunctions or perform routine maintenance services. Even for QA-related adjustments, medical physicists and engineers are usually work together to complete parameter adjustments for achieving the goal of maintaining high quality machine performance.

Conclusions

On-site machine QA audits were implemented from 2016 to 2019 for all radiation therapy units each year. These measurement results have shown high quality machine performance in Taiwan. Advances in technology bring great potential benefits but also more intensive quality checks should be provided. Machine QA is only one part of the comprehensive QA. Accompanying the SMEQA audits, surveys for small field dosimetry, and IMRT and VMAT plan calculation accuracy, and image guided system quality surveys also have been performed. The data is in processing and would soon be published.

Abbreviations

QA
quality assurance; IAEA:International Atomic Energy Agency; IROC-H:Imaging and Radiation Oncology Core-Houston; EQUAL:The ESTRO-QUALity Assurance Network for radiotherapy; DAN:the IAEA Dosimetry Audit Network; SMEQA:Standards for Medical Exposure Quality Assurance; AEC:Atomic Energy Council; HDR:high dose-rate; AAPM:American Association of Physicists in Medicine; NRSL:National Radiation Standard Laboratory; PSDL:primary standards dosimetry laboratory; FFF:flattening-filter-free; CSMPT:Chinese Society of Medical Physics, Taipei.

Declarations

1. Ethics approval and consent to participate: Not applicable, no identifiable individual patient data
2. Consent for publication: Not applicable, no identifiable individual patient data
3. Availability of data and materials: The datasets during and/or analyzed during the current study available from the corresponding author on reasonable request.
4. Competing interests: The authors declared that they have no competing interests.
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7. Authors' contributions: AC Shiau, SM Hsu, CP Chen and SH Fan were responsible for design of the study. PY Huang, CP Chen, YT Huang and KY Lien were responsible for the data acquisition. AC Shiau and SM Hsu were responsible for the analysis and interpretation of data. SC Jeng, HH Chen and JA Liang provided some intellectual content. AC Shiau approved the version to be submitted.

Conflict of Interest Statement:

None of the authors has conflict of interest.

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Tables

Table 1. Procedures and acceptance criteria for on-site quality audits.

A. medical accelerator

Item	Procedure	Criterion
1	X-ray and electron output accuracy	2%
2	X-ray central axis dosimetry parameter consistency	2%
3	Electron central axis dosimetry parameter consistency	2% or 2 mm
4	X-ray beam flatness consistency	2%
5	Electron beam flatness consistency	3%
6	X-ray and electron beam symmetry	3%

B. HDR brachytherapy unit

Item	Procedure	Criterion
1	Source transit velocity consistency	1 sec (from shielded safe to total extension distance)
2	Source strength accuracy	5%
3	Source positioning accuracy	1 mm
4	Timer accuracy	1 sec/min

C. Tomotherapy

Item	Procedure	Criterion
1	X-ray output accuracy	2%
2	X-ray beam central axis dosimetry parameter consistency	2%
3	X-ray beam profile dosimetry parameter consistency	2%
4	Couch vertical/longitudinal motion accuracy	1 mm

D. Cyberknife

Item	Procedure	Criterion
1	X-ray output accuracy	2%
2	X-ray central axis dosimetry parameter consistency	2%
3	X-ray beam flatness consistency	3%
4	X-ray beam symmetry	3%
5	Imaging and treatment coordinate coincidence	1 mm

E. Gamma knife

Item	Procedure	Criterion
1	Photon output accuracy	2%
2	Coincidence of radiation and mechanical isocenter	0.3 mm
3	Timer accuracy	0.01 min

Figures

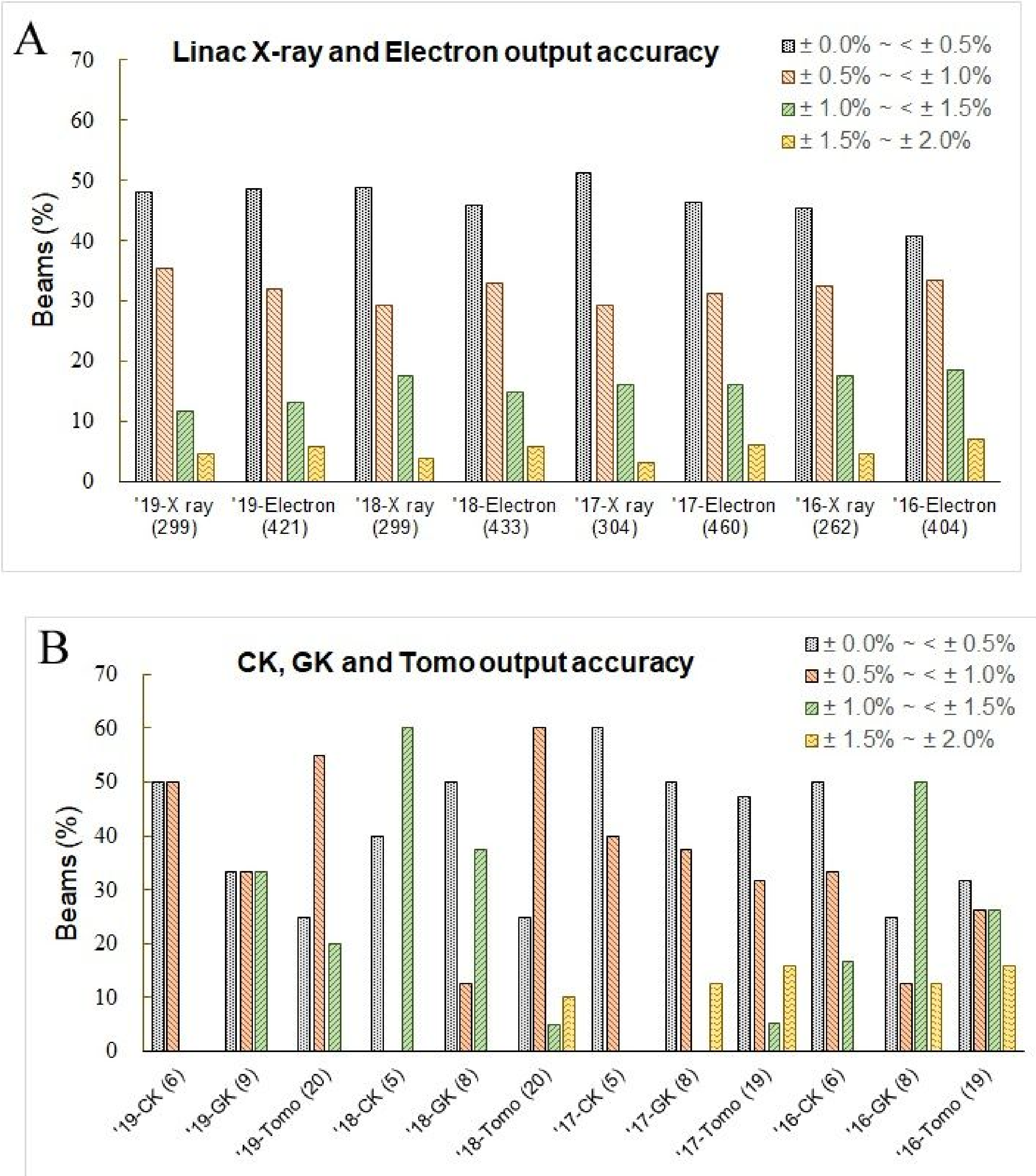
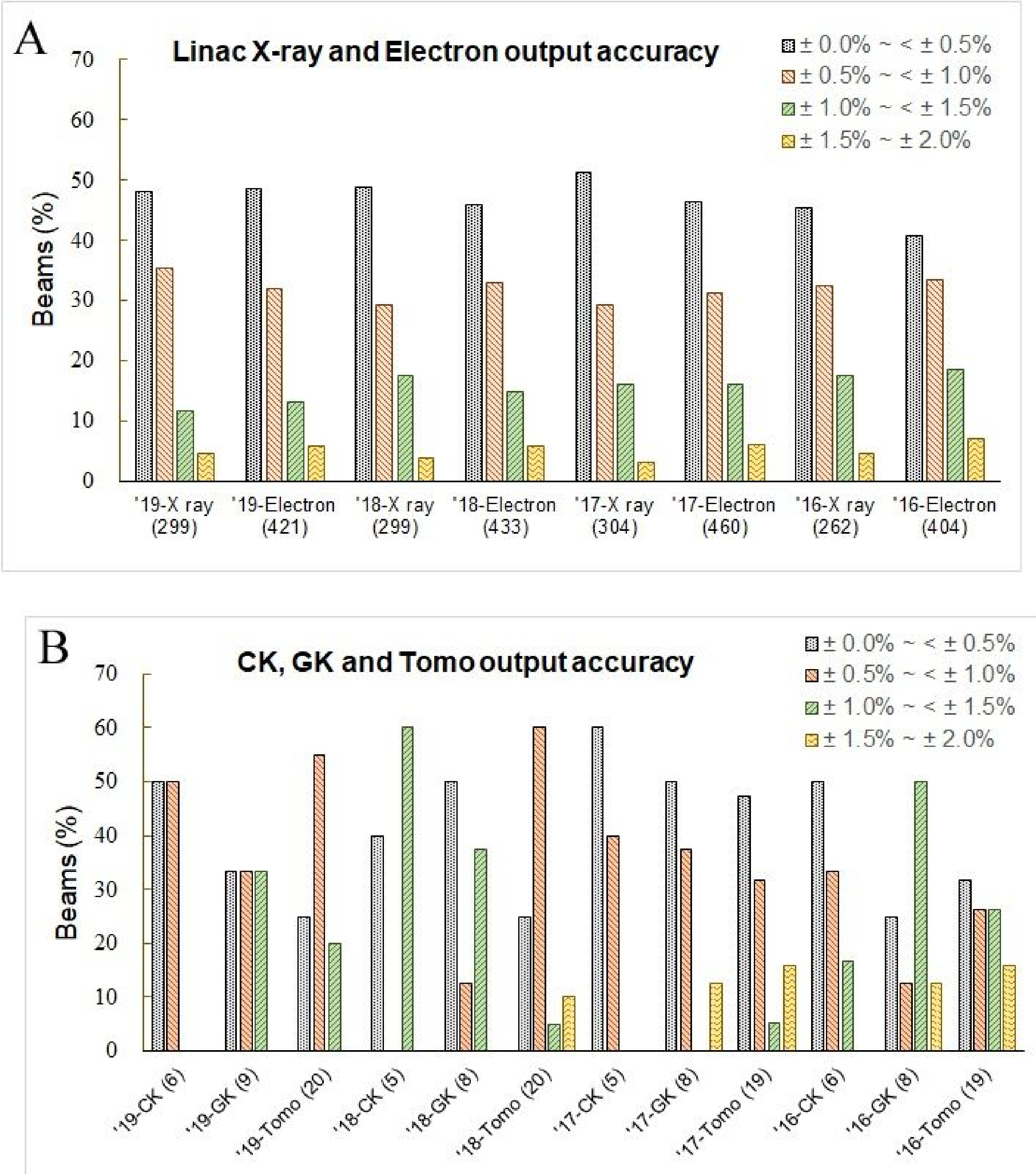


Figure 1

Results for the reference-point measurement showing the distribution of the deviation of the ratio of the measured dose to the stated dose. (A) photon and electron beams from linacs. (B) measurements from Gamma knifes, Cyberknifes and Tomotherapys.



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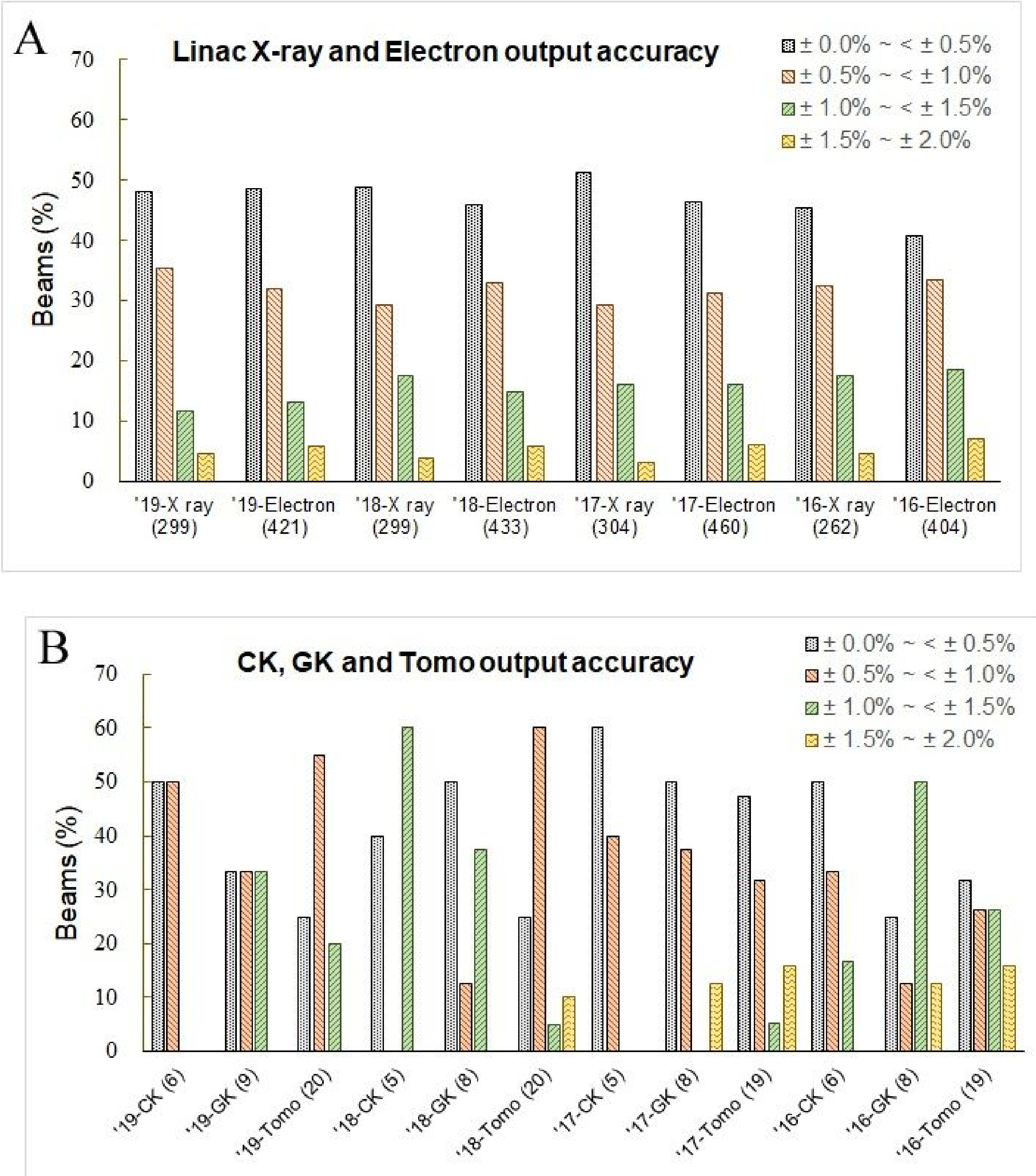

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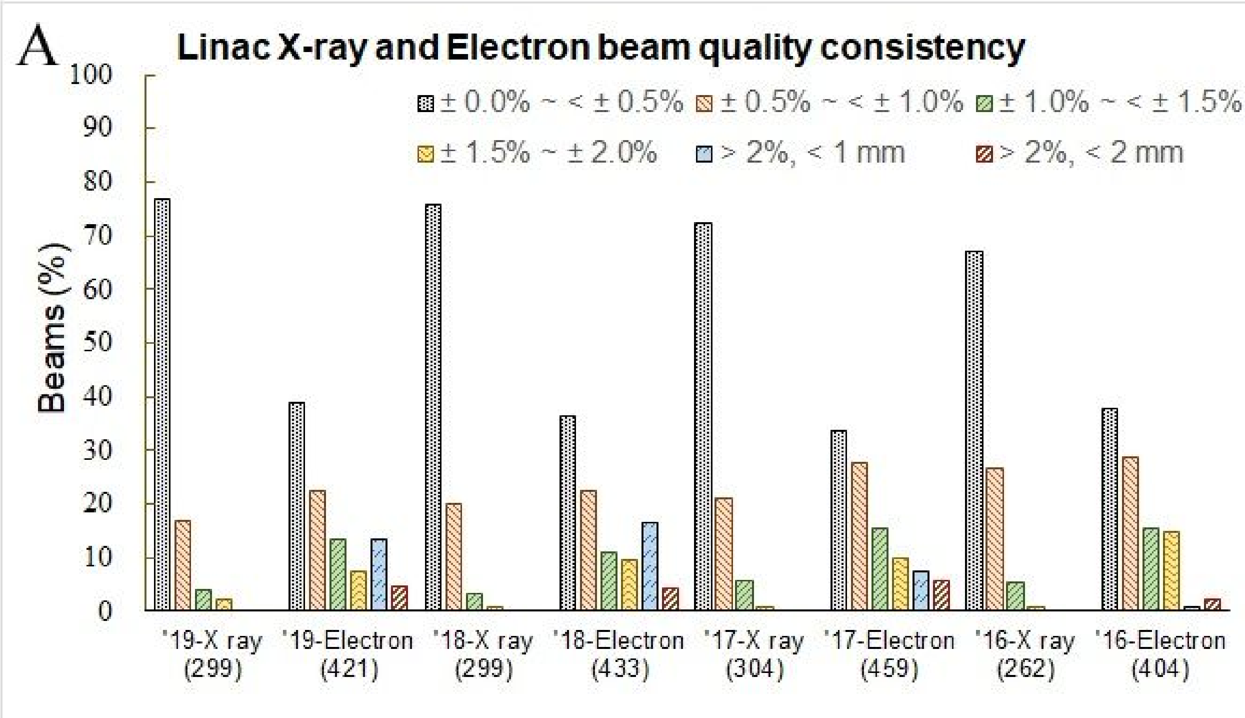


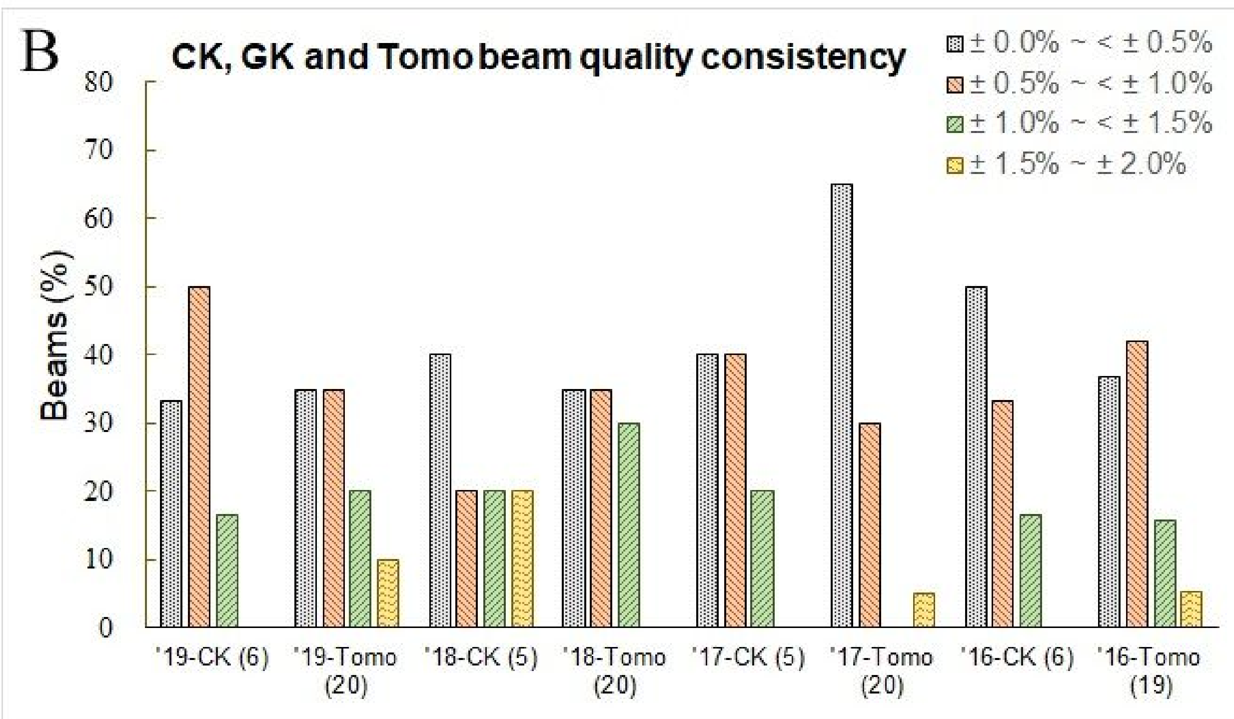
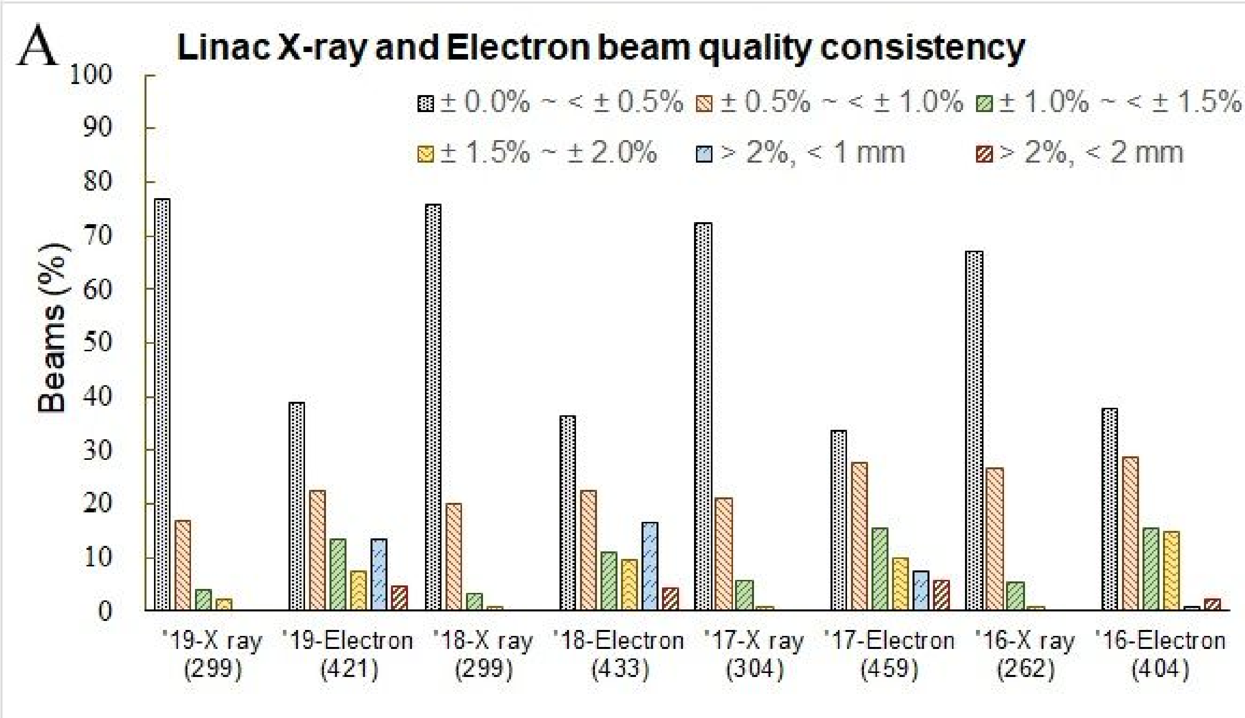
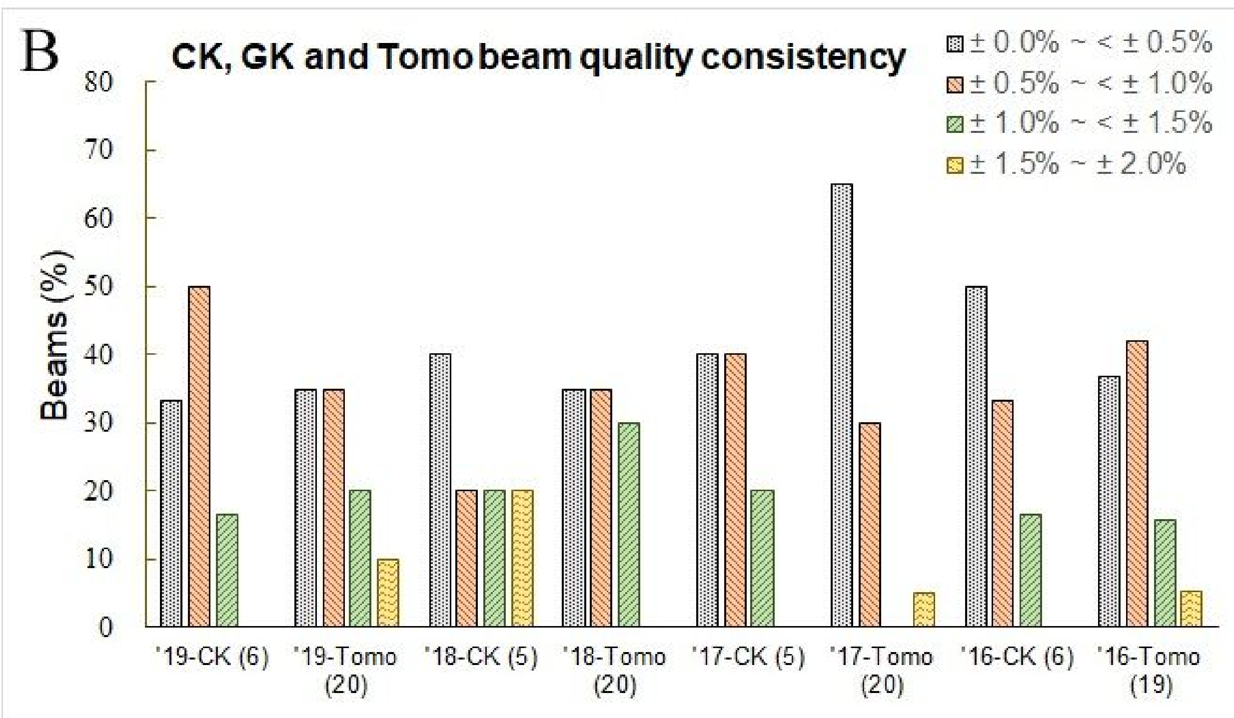


Figure 2

Results for the beam quality measurement. (A) photon and electron beams from linacs. (B) measurements from Gamma knifes, Cyberknifes and Tomotherapys.





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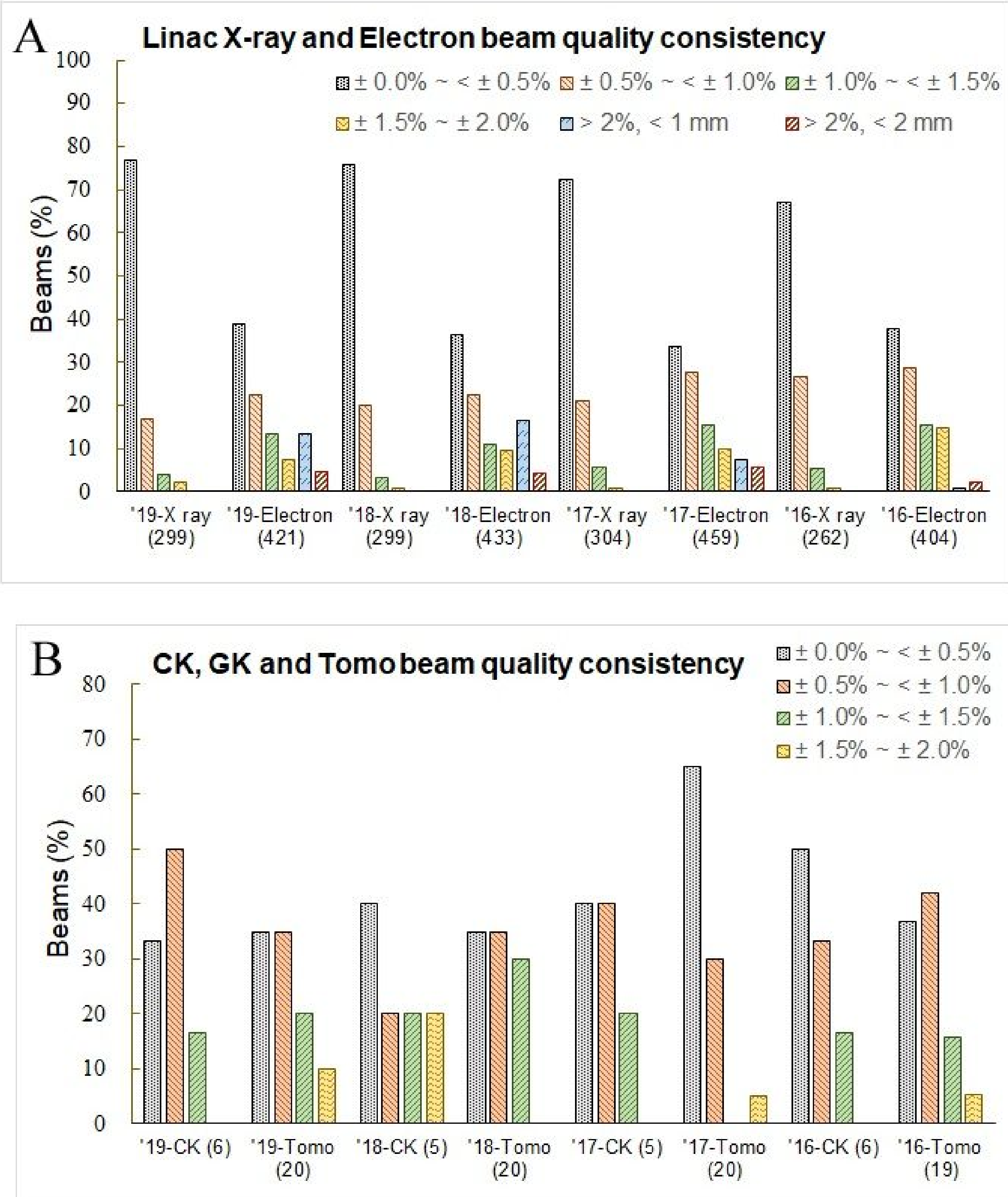

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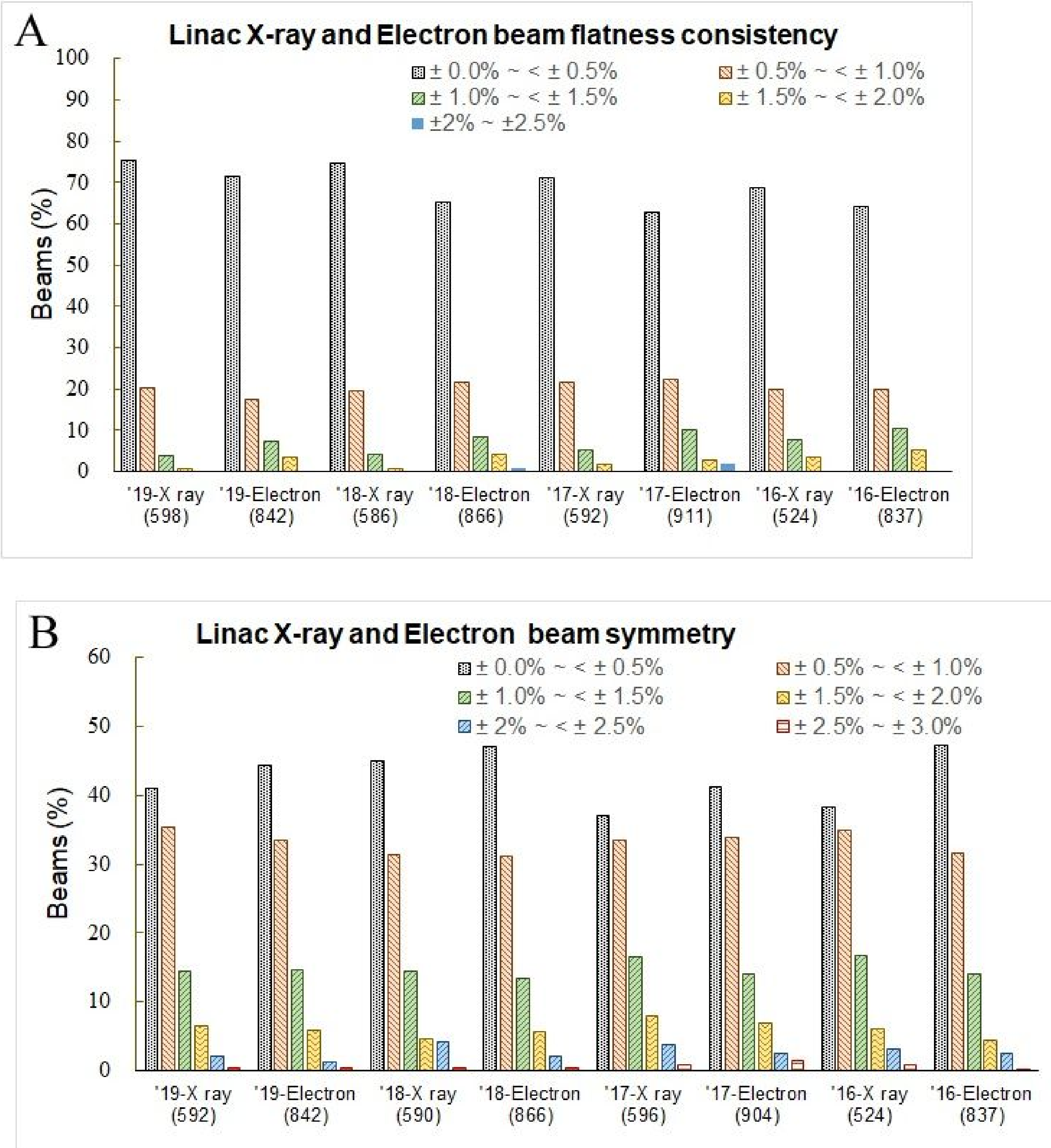
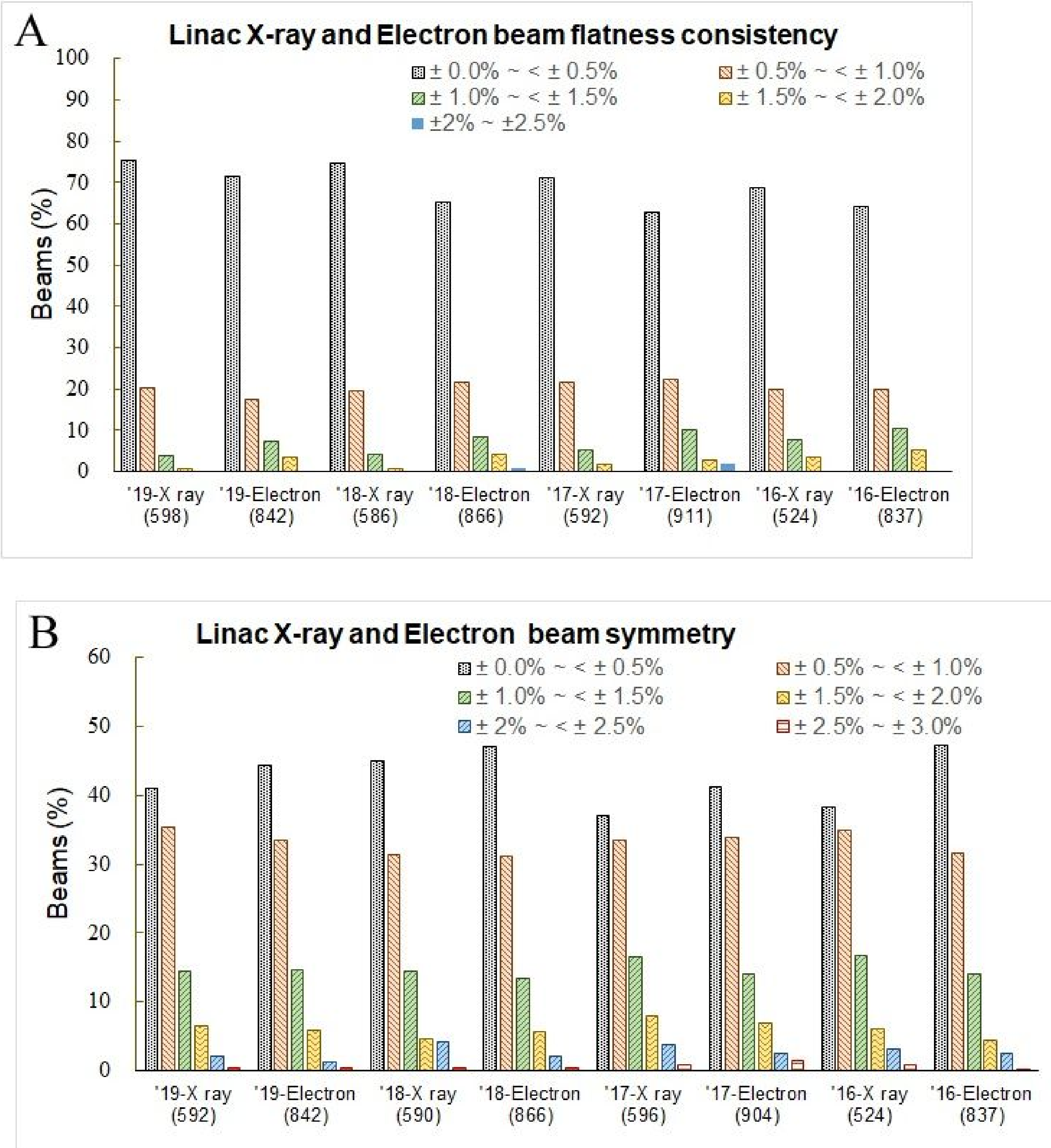


Figure 3

Results for the Beam uniformity measurement for photon and electron beams from linacs. (A) flatness consistency; (B) symmetry.



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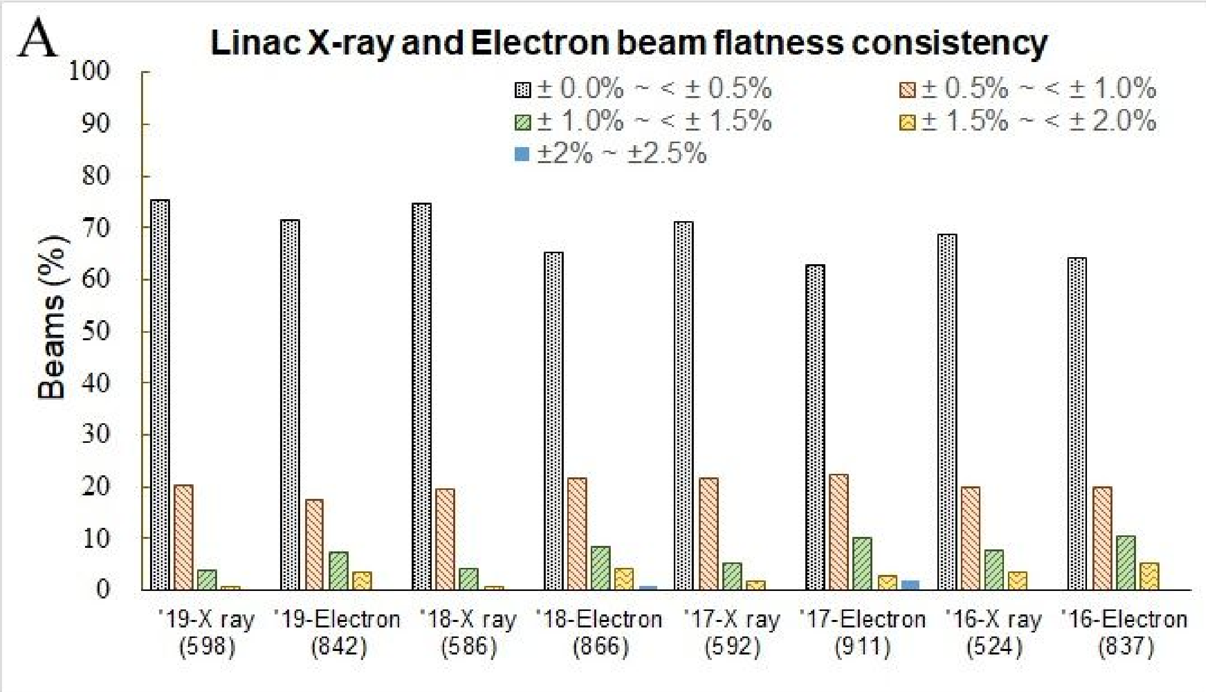

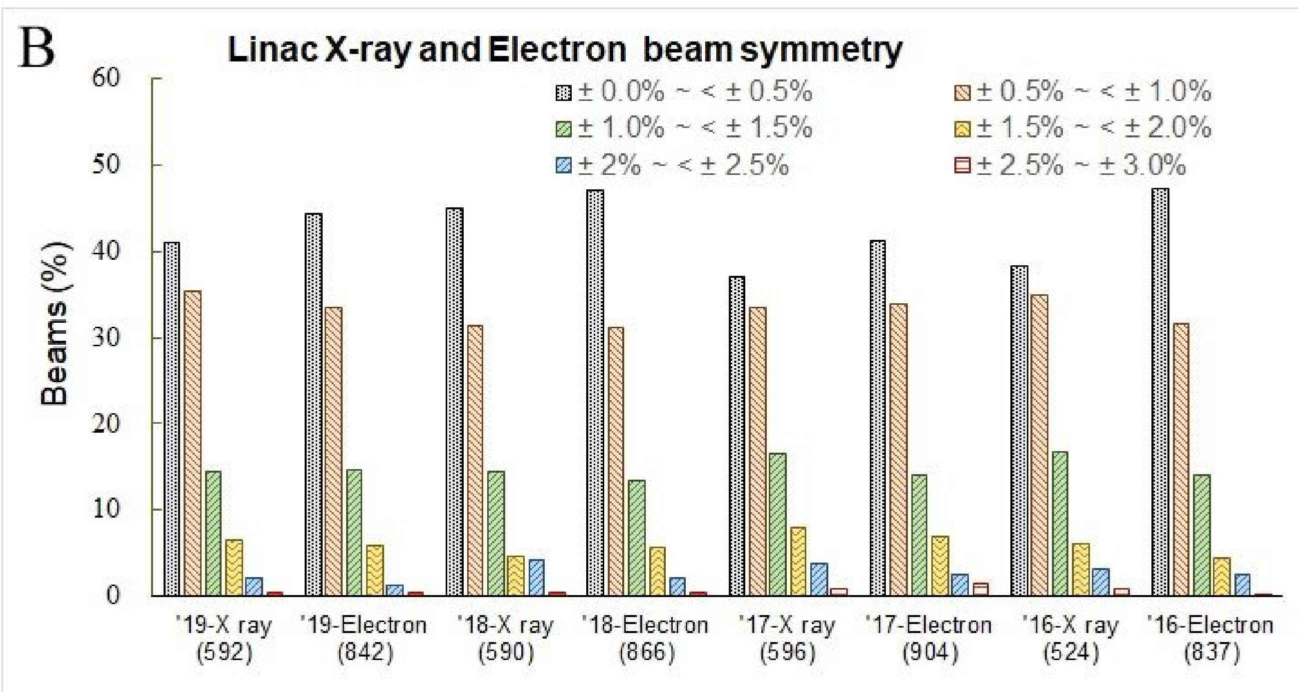

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